The Biomechanics of Exercise Countermeasures
NAGW-4421 (Years 1 & 2) & NAG5-6199 (Year 3)

FINAL REPORT

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BACKGROUND

The Penn State Zero-gravity Simulator (PSZS) is a device developed by the Center for Locomotion Studies (CELOS) to enable ground studies of exercise countermeasures for the bone loss that has been shown to occur during long-term exposure to zero gravity (0G). The PSZS simulates 0G exercise by providing a suspension system that holds an individual in a horizontal (supine) position above the floor in order to enable exercise on a wall-mounted treadmill. Due to this orientation, exercise performed in the PSZS is free of the force of gravity in the direction that would normally contribute to ground reaction forces. In order for movements to be more similar to those in 0G, a constant force suspension of each segment (equal to the segment weight) is provided regardless of limb position. During the preliminary development of the PSZS (supported by NASA grant NAG 9-379), CELOS researchers also designed an optional gravity-replacement simulation feature for the PSZS. This feature was a prototype tethering system that consisted of a spring tension system to pull an exercising individual toward the treadmill. The immediate application of the tethering system was to be the provision of gravity-replacement loading so that exercise in 0G- and 1G-loading conditions could be compared, and the PSZS could then be used to evaluate exercise countermeasures for bone loss during space flight. This tethering system would also be a model for the further refinement of gravity-replacement systems provided for astronaut usage while performing prescribed exercise countermeasures for bone loss during long-term space flights.

OBJECTIVES

The objectives of the research conducted with this award have been:

1) to redesign the gravity replacement loading configuration to increase the load tolerance of individuals exercising in the PSZS with the desired end point being full body weight replacement,

2) to quantify the biomechanical similarities between fully loaded (100%BW) PSZS exercise and 1G exercise, and

3) to make preliminary determinations of localized bone strains in human cadaveric tibia during simulated loading conditions.

YEAR 1 PROGRESS

Phase 1

The first phase of the project was designed to evaluate alternate tethering configurations for the gravity replacement aspects of the PSZS. Eight males who were either students or instructors in the Penn State Navy ROTC program volunteered to be participants in the first phase of this study. They had an average age of 23.62±3.96 years, an average height of 159.12±2.97 cm, and an average mass of 72.33±4.26 kg. These subjects were recruited because they had similar body mass indices and physical activity levels to members of the astronaut corps. Constraints imposed by the PSZS limited subject body mass to less than 80 kg. The braces used to support subjects in the PSZS were not adaptable to most female body types; thus, male subjects were chosen. [Note: The suspension system was later redesigned and women subjects were tested in phase 3 experiments.]

The objective of the first phase was to quantify the ground reaction forces, tethering spring tensions, and subjective comfort ratings from subjects wearing one of four restraint harness designs with a 60% body weight load from the spring tensions while walking or running in the PSZS. The four spring conditions tested were: 1) "no springs," 2) "shoulder springs," 3) "waist springs," and 4) "both (waist and shoulder) springs." The waist harness consisted of a standard mountain climbing harness to which four springs were attached. The shoulder harness, to which four springs were attached, consisted of a pair of modified football shoulder pads. The "waist and shoulder" springs harness consisted of the combination of these two harnesses. Comfort was assessed by a modified Borg-like scale where "0" indicated no discomfort, "4" indicated moderate discomfort, and "10" indicated excruciating pain.

There were great variations in ratings of comfort ($p<0.001$) from subject to subject, which was not surprising due to the fact that people perceive pain differently. The order in which the conditions were presented had little bearing on comfort ($p>0.05$). This implies that subjects could well tolerate being hung in the PSZS because their final condition was no more uncomfortable than the first condition to which they were exposed. In addition to rating overall discomfort, the subjects were also asked how much discomfort they were feeling in their legs, hips, back, and shoulders. Tethering subjects by the waist caused discomfort in their legs, hips, and back. Not being tethered at the shoulders reduced discomfort in the shoulders. Similarly, not being tethered at the waist reduced discomfort at the waist. Not surprisingly, tethering subjects by the waist and shoulders, i.e. the "both springs" condition, was the most comfortable condition.

Spring tension variability was also evaluated during this phase of research. The spring tensions appeared to remain similar across conditions, regardless of the harness configuration worn by the subject. To allow for comparison between subjects, the spring tension variables from each subject were divided by that subject's body weight, thus "normalizing" the variables. The only factor that was significantly different was tension fluctuation, which increased in the "both springs" condition ($p = 0.004$). It was apparent during the testing of the "both springs" condition that there were times in a typical gait cycle when the springs lost all tension. This observation was verified on the videotapes of the spring experiments. Because eight springs were used, this condition was such that the springs did not have to be stretched far in order to reach a tension of 60% of body weight. Thus, the large fluctuation is a result of this loss in tension in the springs, whereas the springs never lost their tension in the "shoulder springs" and "waist springs" conditions. The order in which treatments were administered did not affect the tension in the springs.

The maximum ground reaction forces were highest in the "shoulder springs" condition ($p=0.002$). Likewise, the impulse, or the area under the ground reaction force curve, was also significantly higher in the "shoulder springs" condition ($p=0.001$). The following variables were significantly different between subjects ($p < 0.05$) and were not affected by the condition or the order in which the conditions were administered: contact time, impact force, time to maximum impact peak, and loading rate.

In summary, it was determined during Year 1 that the ground reaction forces were highest in the "shoulder springs" condition, but the reason for this is not clear. There were no differences in the average tensions between any of the spring conditions, although the average maximum tension and the amount of tension fluctuation was highest in the "both springs" condition. The comfort data showed that subjects complained of back, hip, and leg pain when the waist was tethered. Although no kinematic analysis was performed of the motion of the subject walking or running on the treadmill, it can be speculated that greater ground reaction forces were produced in the "shoulder springs" condition because the subjects felt freer to move their legs, taking longer, bigger strides, and thus producing higher ground reaction forces. Because the subjects frequently objected to the discomfort associated with waist spring attachment sites at the hips and because this fact clearly did affect the ground reaction forces, the location of the attachment of the carabiners were moved to another area in the hip region so that the subject was not in such discomfort. The new attachment site for the carabiners was also selected to make certain that the legs are unencumbered.

The unanswered question arising from these preliminary experiments was a determination of the reason that the "both springs" condition was the most comfortable. The "both springs" condition caused the tethering load to be distributed over a larger area of the body, but it also resulted in small time intervals during which certain springs were not stretched such that smaller tethering force might be felt. Because the average tensions were the same in all of the conditions, the first possibility is most likely the one that is true. However, this could not be proven until another experiment was performed in which the load in the tethering springs was increased to a point when the springs always have a tension.

The order in which the treatments were given was not a significant factor in the comfort or spring tension data, but it was significant in some of the ground reaction force data. Subjects apparently needed time to get acclimated to the unusual task being required of them (i.e. being lifted by the PSZS, being pulled by the spring harness system, and having to run on a treadmill on the wall), and the ground reaction force data thus shows a minor order effect.

In summary, the comfort data, spring tensions, and ground reaction forces would have lead to different conclusions as to which harness design was the most effective if considered separately. Therefore, it was determined that all of the factors have to be carefully considered in concert with one another when choosing a harness design for a gravity replacement system. However, bone demineralization is thought to occur in response to a lack of impact forces or the lack of high loading rates applied to the lower extremity. Thus, ground reaction forces were considered to be an integral part in the decision to choose a particular harness design.

Phase 2

The objective of the second phase of the experiment was to measure the ground reaction forces, tensions in the tethering springs, and subjective ratings of comfort from subjects running with gravity replacement loads (GRL) 60%, 80%, or 100% body weight applied from either the "waist and shoulder" springs harness (WSO) or the "shoulder springs" harness (SSO). This objective was met with two successive experiments.

Harness comfort was first evaluated using eight subjects running at 2.0 ms-1 for 3 minutes at each level of the GRL in the PSZS wearing each harness design. Subjective ratings of harness comfort, ground reaction forces, and GRL data were collected during the final minute of exercise. The results showed that 100% BW loading conditions were comfortably tolerated, although discomfort increased as the GRL increased. There were no differences in perceived comfort between harnesses using the newest harness design. The weight acceptance rate and the first and second peaks of the ground reaction force increased with increasing levels of the GRL, and subjects were able to tolerate a GRL of 100% BW well. The magnitude of the ground reaction force peaks and the weight acceptance rate were found to be related directly to the magnitude of the GRL.

A second experiment investigated ground reaction forces in both harness conditions. Ground reaction forces were measured during overground walking ($1.35\ m \cdot s^{-1}$) and running ($2.68\ m \cdot s^{-1}$) and fully-loaded locomotion at the same speeds in two restraint harness designs in the PSZS. Load cells measured the magnitude of the gravity replacement load in the PSZS conditions. It was determined from these experiments that maximum active forces were greater in overground walking and running than in the PSZS; however, weight acceptance rates were greater in the PSZS running conditions than in overground running. Large loads and rates of change of load were found to be generated at the feet during simulated zero gravity exercise, and further investigation was needed to determine whether these loads would be sufficient countermeasures to bone loss when used in an appropriate exercise program in space. The refinement of the gravity replacement system to provide a constant 1G load was, thus, a factor that was identified as requiring continued consideration during future design modifications.

YEAR 2 PROGRESS

The next phase of the study was designed to quantify the biomechanical similarities between fully loaded (100%BW) PSZS exercise and 1G exercise. Ground reaction forces, lower extremity joint movements, and electromyographic data were collected on 16 subjects during walking and running in four experimental conditions. Normal overground locomotion and locomotion on a conventional treadmill were the two "1G" conditions. Loads in the tethering harnesses were compared between the "shoulder springs only" and "waist and shoulder springs" conditions.

Each subject was instrumented with electrogoniometers aligned to the ankle, knee, and hip to quantify joint motion. Electromyographic electrodes were placed on the subject's left tibialis anterior, gastrocnemius, rectus femoris, vastus lateralis, biceps femoris, and gluteus maximus muscles to quantify the muscular activations. These electromyographic and joint kinematic data were then combined to determine the phases of isometric, concentric, and eccentric activations of each of the six muscles.

The average tensions in the tethering springs were slightly greater than body weight during walking in the two PSZS conditions and slightly less than body weight in the PSZS running conditions. The tension fluctuations were 13% and 18% of body weight in the "shoulder springs only" condition during walking and running respectively, and 22% and 36% of body weight in the "waist and shoulder springs" condition. It appears as if these fluctuations were related to many of the biomechanical differences between the 1G and PSZS conditions in the kinematic, ground reaction force, and electromyographic variables.

The major finding of the kinematic data was that in the PSZS, subjects had a tendency to "groucho" walk and run with their knees significantly more flexed ($p<0.05$) than during the "1G" conditions. In the stance phase of overground running, the knee was flexed to an average of 6.96° whereas in the PSZS, the average knee stance phase flexion was 11.72° (0° was considered a straight leg). This was most likely an attempt to reduce the discomfort of the tethering springs pulling on the body. The more the subjects' knees were flexed, the less the springs were stretched, thus reducing the tension.

The maximum ground reaction force ($p<0.05$) and the impulse ($p<0.005$) were significantly less in the PSZS conditions, although the rate at which the initial ground reaction force was applied in the PSZS conditions was greater than in the "1G" conditions ($p<0.05$). However, if the ground reaction force data was normalized to subject load instead of body weight, the ground reaction force curves were remarkably similar, with no differences in the maximum ground reaction force or the impulse. At the time of the maximum ground reaction force, the loads in the tethering harness were near their minimum. In the PSZS, the subjects did not have to push off with as much force as was required during the overground condition in order to propel themselves forward.

The muscular activations, in terms of the areas under the full-wave rectified EMG, of the tibialis anterior, gastrocnemius, rectus femoris, vastus lateralis were significantly greater in the PSZS conditions than in the 1G conditions ($p<0.004$). The timing of the muscular activations was similar between conditions, but the intensity of activation was greater in the PSZS. The activations of the biceps femoris and gluteus maximus were not affected by the experimental condition. It is therefore reasonable to assume that tethered treadmill exercise provides a sufficient countermeasure to the atrophy of these 6 muscles during spaceflight. The patterns of isometric, concentric, and eccentric activations were similar between conditions.

Researchers do not agree on the necessary stimulus for maintaining bone mass in space, and this uncertainty prevents clear conclusions to be drawn on the effectiveness of treadmill exercise in space. If high loading rates applied to the lower extremity are the crucial stimulus, then tethered treadmill exercise under 100% BW tethering load should prove to be a sufficient exercise countermeasure. However, if it is the maximum amount of force applied to the lower extremity that maintains bone homeostasis, then tethered treadmill exercise will prove ineffective unless the maximum ground reaction forces seen during overground running can be replicated during tethered exercise in spaceflight. However, it is clear thatmore attention must be paid to the manner in which the subject is tethered to the treadmill in order to provide the maximum benefits of treadmill exercise during spaceflight. Future work will be aimed at minimizing the fluctuation in the tethering springs so as to more closely resemble the constant pull of gravity, thus requiring the exercising person to "push off" the treadmill with a force of approximately 2-3 times body weight in running. Also, an attempt to minimize the harness discomfort in order to lessen the subjects' desire to "groucho" walk and run would also result in increased maximum ground reaction forces.

YEAR 3 PROGRESS

Assuming that bone homeostasis is modulated by strain-related factors, it is likely that the success of treadmill exercise countermeasures will be dependent on the magnitude of the gravity replacement loads (GRLs) used. It is possible that subject discomfort may prevent the use of 1G load substitution. However, the relationship between GRL and bone strain is also unknown. Thus, a new protocol was developed in the final year of the project to allow information gathered from human studies using the PSZS to be compared with bone strain data. The dynamic gait simulator (DGS), a unique cadaver modeling system, was used to measure dynamic bone strains at the human distal tibia under a representative range of GRLs in order to better predict the dose-response relationship between treadmill exercise in micro-gravity and localized bone strains. The DGS was used to provide dynamic loading of cadaveric limb preparations and mimic the kinetics and kinematics of the tibia, foot, and ankle during the stance phase of gait from heel-strike to toe-off. Physiologic actions of the extrinsic foot muscles are simulated using force feedback controlled linear actuators interfaced with the tendons of the specimen. Previous studies have shown that the ground reaction forces and plantar pressures under the specimens are well within physiologic ranges and demonstrate inter-subject variation consistent with that seen in live subjects. The timing and force output of six separate muscle groups (constituting the major dorsi- and plantar-flexors of the foot) were independently controlled with stepper motor-powered linear actuators. Thus, the PSZS and the DGS were combined to enable studies of the implications of exercise for maintaining bone quality during space flight.

Using the DGS system, we found bone strains to be linearly related to external GRLs ($R^2>0.75$) and established equations whereby strain stimuli at given locations can be calculated from external loads. The distribution of strains indicates that the primary mode of tibial loading is in bending, with little variation in the neutral axis over the stance phase of gait. The greatest maximum (tensile) and minimum (comprehensive) principal strains were found to develop on the anterior crest and posterior aspect of the tibia, respectively. The relative strain response to a given GRL dosage was found to be site-specific, with the largest dose-response gradient occurring at the anterior and posterior sites furthest removed from the neutral axis of bending.

Thus, using a robust cadaver model, we have been able to show in a small group of cadaver legs that decreased GRLs produce proportional linear decrements in tibial strains. More than 75% of the variance in internal bone strain response was explained by external gravity replacement load (which was also proportional to external ground reaction force). Predictive dose-response equations have been developed through which a strain stimulus at a given site may be computed for any GRL. The overall peak strain for each condition was compressive and occurred along the posterio-medial border of the tibial cross section. Maximum tensile strains occurred anteriorly on the tibial crest. The distribution of tensile and compressive strains and the relative invariance of the neutral axis orientation over the stance phase indicate that the primary mode of loading at the distal tibia is bending, with muscle forces (notably the triceps surae) acting as the principal modulators of bone strain. Additionally, peak strains occur at sites other than those typically measured in live human subjects.

Our data suggest that *in-situ* bone strains can be reliably related to the external-loading environment. It is reasonable to assume, therefore, that previously proposed equations could be use to calculate a theoretical bone maintenance stimulus using only GRL as input. This relationship is important for understanding the theoretical potential and most effective implementation of various exercise countermeasures to bone loss during space flight.

<u>RELATED PRODUCTIVITY & SUPPORT</u>

Year 1 Intramural Funding:

Dr. Cavanagh and Dr. Derr acquired additional support during Year 1 of the project through two intramural awards from the Pennsylvania Space Grant Consortium.

The first intramural award was obtained under the STIR (Stimulating Interdisciplinary Research) program. This program is designed to strengthen interdisciplinary collaborations in research, and the small award made to Drs. Cavanagh and Derr enabled the formation of a solid interdisciplinary student support team for the PSZS project. The award provided funds which enabled Jean McCrory (who was partially supported under main NASA project award) to be assigned to this research on a year-round basis. In addition, it provided a semester of support for Sandy Balkan (Graduate Assistant, Statistics) and provided hourly summer wages for two undergraduate students, Heidi Baron (Exercise and Sports Science) and Brian D'Archangelo (Mechanical Engineering). Because this project provided a single source of funding for students from three different units representing three different Penn State colleges, faculty and students from extremely diverse disciplines were provided a forum for direct interaction and at the same time enhanced ongoing efforts.

Year 2 Intramural Funding

An intramural award was obtained through the Minority Undergraduate Research Assignments (MURA) Program funded by NASA at Penn State, which is designed to increase involvement of minority freshmen in NASA-related projects with the ultimate goal of increasing retention of these students in science and engineering programs. MURA has provided hourly wages and related support to enable the involvement of Aquilah Couvson, a Penn State freshman, to participate in this project and gain research experience and exposure.

Jean McCrory received a $200 dissertation grant from the Penn State College of Health and Human Development, which covered additional supplies and materials for aspects of the project, that contributed specifically toward her associated dissertation research.

The Pennsylvania Space Grant Consortium has also awarded an $8,000 grant to CELOS through the STIR Program (Stimulating Interdisciplinary Research) to provide wages for two undergraduate senior honors students and two graduate assistants from the Departments of Kinesiology and Statistics to receive compensation to work during the Summer of 1997 on evaluations of various exercise countermeasures performed by Russian cosmonauts during space flight.

Year 2 Extramural Funding

The Center for Locomotion Studies concurrently performed contracted evaluations for Wyle Laboratories (formerly Krug Life Sciences) under a proposal entitled, "Verification Experiments for the Treadmill Vibration Isolation and Stabilization System (TVIS)." This contract included four tasks as follows: Task 1: SLD and Harness Verification - Ground Based Studies; Task 2: Stability of TVIS - Ground Based Studies; Task 3: Stability of TVIS - Flight Expert Analysis; and Task 4: Biomechanics of Locomotion on TVIS - Ground Based.

Year 3 Extramural Funding

A proposal that was submitted in response to NRA 96-HEDS-04 from the NASA Gravitational Biology and Biomedical Research and Countermeasures Program was funded during the final period of support for this grant. That proposal will provide funding to continue the current line of investigation to enable ground validation and subsequent implementation in the International Space Station of biomechanical experiments designed using the PSZS to provide further insight into reasons for loss of bone mineral during prolonged exposure to microgravity.

Other Activities

Dr. Peter R. Cavanagh is member of the Science Working Group for the International Space Station Human Research Facility and a member of the NASA US-Russian Working Group on the International Space Station Treadmill.

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